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(71)(72) Applicants and Inventors: PATTON, John, T. [US/US]; 2955 McDowell, Las Cruces, NM 88005 (US). SHOUMAN, Ahmad, R. [US/US]; 1006 Bloomdale Street, Las Cruces, NM 88005 (US).

(74) Agent: LIDD, Francis, J.; Vapor Corporation, 6420 West Howard Street, Chicago, IL 60648 (US).

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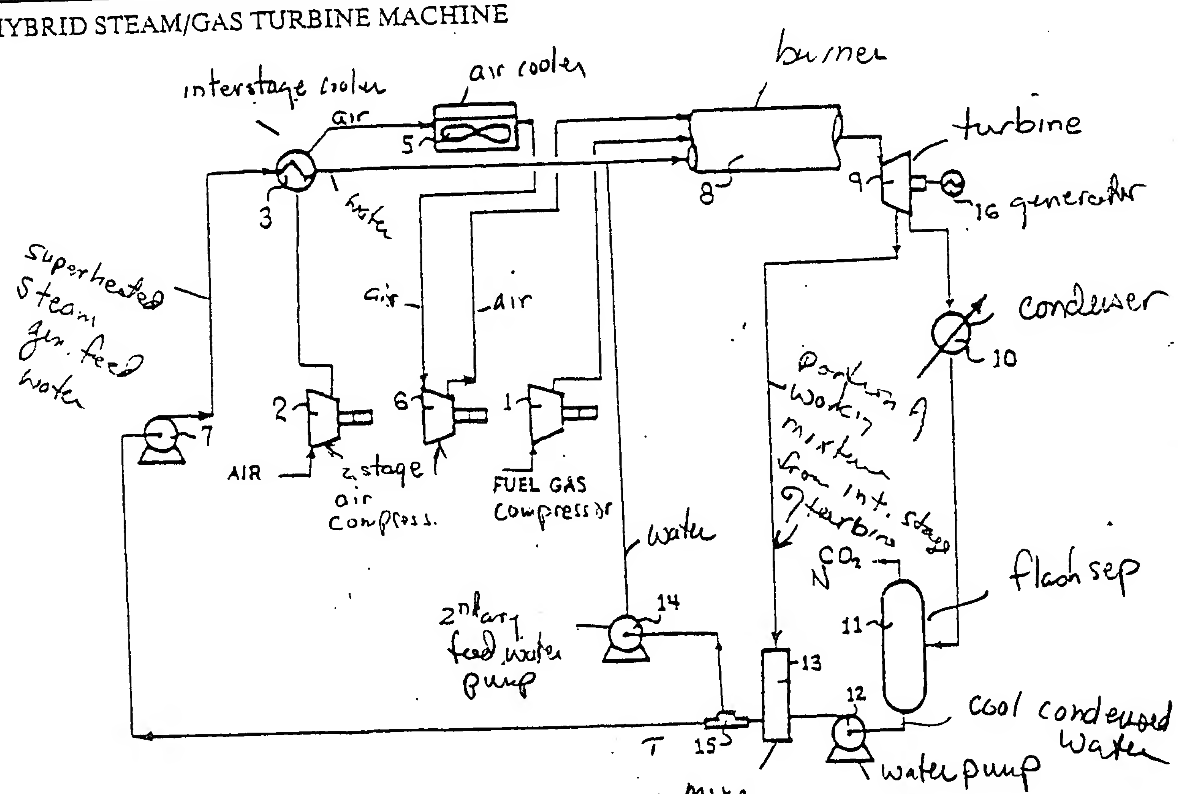
(54) Title: HYBRID STEAM/GAS TURBINE MACHINE



(57) Abstract

An improved thermal efficiency machine (9) for converting fuel to shaft horsepower that utilizes direct water quenching of hot combustion gases (8) to virtually eliminate NO_x pollution present in exhaust emissions from a gas turbine power plant. Combustion is accomplished (9) near the stoichiometric oxygen/fuel ratio to minimize the consumption of expensive oxygen or air. When air (2) is used, the power output (16) of the plant can be increased by injecting purified oxygen in the air stream.

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HYBRID STEAM/GAS TURBINE MACHINE

Background of the Invention

The present invention relates to a unique gas turbine system designed to eliminate the emission of the common pollutant, NO_x. More particularly, the invention relates to a new concept in combustion chamber design which produces the hot gases necessary to generate useful energy when passed through a conventional gas (steam) turbine. The uniqueness of the design allows fuel to be burned with the optimum fuel/oxygen ratio, close to stoichiometric proportions, with the heat thereby generated used to produce superheated steam by direct contact of the combustion products and water, liquid or vapor. This provides a significant reduction in the quantity of oxygen normally required in the conventional combustion chamber used in conjunction with gas turbines. This concept has broad applications and can be used effectively in the design of stationary gas turbines utilized for the conventional production of electrical power, small gas turbines used in specialized applications and often in remote locations such as off-shore drilling rigs, pipe line stations, and co-generation plants.

In 1977 the Environmental Protection Agency issued standards to implement the Clean Air Act with regard to reducing emissions for gas turbine combustion systems. Combustion systems, commonly employed at that time, produced exhaust gases containing as much as 250 ppm NO_x, a level estimated to generate a polluting level of 270,000 tons/year during 1982. In an effort to comply with EPA regulations, the gas turbine manufacturers instituted a significant research effort to define the causes of NO_x generation and effect design changes to reduce NO_x emissions to the lowest practical level. The results of these efforts has been significant. Gas

turbine combustion systems are now available in which the production of NO_x emissions has been reduced by 70 percent from earlier levels bringing current machines into the compliance of the EPA regulations of 75 ppm. The reduction in emissions was achieved following recognition of the key factors responsible for the formation of NO_x in the combustion system. These factors have been well documented and are dominated by two key variables, reaction zone temperature and fuel/oxygen ratio. NO_x is known to be produced according to the following reaction:

$$N_2 + xO_2 = 2NO_x$$

From the above equation it is obvious that both elements, nitrogen and oxygen, must be present in the reaction zone in order for NO_x to be generated. Although the major source of nitrogen is the combustion air supplied to the reaction zone, nitrogen contained in the fuel itself is available for transformation to NO_x under the proper conditions.

To achieve reductions in NO_x emissions required by the EPA in many metropolitan areas it is necessary to resort to catalytic reduction of NO_x with NH_3. This is an expensive solution and at best only ninety percent effective. Significant elimination of NO_x pollution can only be achieved by reducing the amount of nitrogen present in the combustion zone or, better still, eliminating it completely.

Summary of the Invention

Although the high level NO_x emissions from gas turbines have been recognized to be deleterious to the environment for many years, prior efforts to reduce these emissions to an acceptable level have been less than successful. Accordingly, it is the principle objective of this invention to provide a new and improved design concept involving the gases supplied to the combustor for

a gas turbine. This design has the potential to eliminate the production of the pollutant, NO_x, while at the same time not detract from the overall thermal efficiency of the machine. To accomplish the objective of this invention, the combustor is designed to effect the burning of fuel with a near stoichiometric amount of oxygen (air) and by so doing greatly minimizes the production of NO_x. In order to avoid damage to the turbine machinery, the combustion gases, according to this invention, are cooled directly by injecting water or steam into the hot combustion gases. Alternatively, a portion of the water (steam) can be mixed with the fuel prior to its contact with oxygen and the resulting combustion reaction.

The unique feature, distinguishing this invention from the prior art, is the quantity of water injected into the combustor for the purpose of lowering the temperature of the exhaust gases so as to avoid exceeding the metallurgical limits of the turbine machinery. The conventional gas turbine machine uses large volumes of excess air and a <u>small</u> amount of water to achieve the desired exit temperature of the combustion gases. In this invention, little or no excess air is employed and a <u>large</u> amount of water is utilized to achieve the desired exit gas temperature. Approximately two to six pounds of liquid water should be added for each pound of oxygen consumed in the combustion reaction. In applications where water is added in the gaseous phase (steam) the ratio of water to oxygen consumed may be as high as 15 pounds of water for each pound of oxygen consumed.

Unlike the conventional gas turbine which has a thermodynamic optimum at a compression ratio of approximately 15. The present invention increases the optimum compression ratio significantly. In the case of air a compression ratio of 40 is approximately optimum and

ratios below 34 (500 psia) show little advantage. In instances where pure oxygen is used instead of compressed air, the optimum compression ratio is further elevated; well in excess of 200. The overall improvement in thermal conversion efficiency is dramatic. In the case of air combustion the conversion of heat energy to electrical power can approach 50% assuming the temperature of the gas entering the turbine is above about 1600°F. In the case of pure oxygen combustion the conversion efficiency is further increased to approximately 60 percent. By comparison, the conventional gas turbine has a thermal efficiency of only 28 percent and, hence, the application of this invention has the potential for reducing the fuel consumed in the production of electric power by a factor of 20 to 45 percent.

Obviously, achieving the high overall compression ratios indicated above will require several stages of compression. As the compression process proceeds it becomes advantageous and, indeed, desirable to provide for interstage cooling between the compression stages. Such cooling adds significantly to the efficiency of the compression process and the heat rejected in the intercoolers can be used advantageously to elevate the temperature of the water which is subsequently injected into the combustion chamber. Although interstage cooling is not a new concept, nor considered inventive by itself, it is a recognized fact that interstage cooling is not commercially employed in conventional gas turbine machinery because of the high pressure losses associated with the cooling of low pressure gases conventionally used in a gas turbine combustion cycle. It is the very high pressures associated with the current invention that allow the advantageous use of interstage cooling and in essence, this becomes an integral part of the invention.

This invention produces a high pressure, high temperature vapor stream which can be utilized as a source of power by passing through a turbine. This stream will usually consist of approximately 40 - 95% steam and as such has many of the characteristics well recognized by those skilled in the art of steam turbine power generation. A distinguishing feature of this invention is the fact that said steam mixture is produced without the use of an expensive, high pressure boiler, an integral part of all conventional power plants. Elimination of the conventional boiler provides this invention with a significant cost advantage over conventional technology in addition to providing the improved thermodynamic efficiency so desirable in the production of the large quantities of electricity needed to sustain a modern industrial society. This invention is particularly applicable to increasing the capacity and improving the efficiency of a conventional power plant by utilizing the direct contact heat exchanger to produce superheated steam at a greatly elevated temperature that subsequently passes through the turbine to produce power.

Detailed Description and Preferred Embodiments of the Invention

As indicated above, the present invention relates to the design of a hybrid steam/gas turbine machine that utilizes a direct contact superheated steam generator consisting of a combustion chamber that provides for fuel to be burned with a near stoichiometric quantity of oxygen and the extreme flame temperatures, so generated, mitigated by direct heat transfer to a secondary fluid, water or steam. The fuel supplied to the combustion chamber can be either gaseous or liquid but, preferably, should be burned completely without the formation of any particulate matter that could subsequently damage the gas

turbine. It is preferable for the oxygen (air) supplied to the combustion chamber to be well mixed with the fuel in the combustion zone and, in the case of liquid fuels, vaporization of the fuel prior to entering the combustion zone has been found to be advantageous.

The operating temperature limit of conventional gas turbines is approximately 2000°F. The gases generated in the improved combustion chamber could approach 5000°F and, hence, must be cooled prior to passage through the gas turbine machinery. This is accomplished, according to the current invention, by direct cooling or quenching of the combustion gases by injection of water or steam into or immediately downstream of the combustion zone. In applications wherein water is selected as the quenchant, it is expected that complete vaporization will often occur. Said vaporization and the attendent heat absorbed by the water in the process minimizes the mass of the injected quenchant required to achieve the desired exit temperature of gases exiting the combustion chamber and subsequently entering the gas turbine.

The mixture of gases exiting the turbine predominantly, steam, nitrogen and carbon dioxide, can be partially condensed to maximize the energy output of the turbine. Alternatively, the turbine exhaust gas can be utilized as a source of process heat or injected into a subsurface formation to enhance the production of petroleum, salt or other minerals.

Unlike conventional gas turbine machines whose power output is modulated by adjusting the flow of fuel to the combustor, the power output of this invention can be further adjusted by supplying the combustor with air enriched with oxygen, said adjustment being accomplished by varying the degree of enrichment (oxygen content) of the air so supplied.

The process of the present invention can be better understood by reference to the following specific but illustrative example.

Example 1

The process for utilizing the direct contact superheated steam generator for the purpose of producing electric power is depicted in Figure 1. The turbo machinery consists of an expanding turbine (9), a fuel gas compressor (1) and two-stages of air compression (2) and (6). The following illustration is based on an electric power generation plant utilizing this inventive process and rated at 130 megawatts. To effect the production of electricity 1487 Mcf per hour of natural gas is fed to compressor 1, a multi-stage machine that compresses the natural gas to 1470 psia thereby enabling it to be injected into the burner, an integral part of the direct contact superheated steam generator (8). Simultaneously, 14,156 Mcf of air are fed to the first stage of air compressor (2) where the pressure is elevated adiabatically to 147 psia and the temperature due to the work of compression is simultaneously elevated to 713°F. The hot compressed air is passed through an interstage cooler (3) where it is cooled by heat exchange with a portion of the superheated steam generator feed water (220,000 lb/hr) whereby the superheated steam generator feed water is elevated in temperature to 700°F while the compressed air is simultaneously being reduced in temperature to 382°F. The partially cooled compressed air passes through an air cooler (5) where the temperature is further reduced to 100°F. The cooled, partially compressed air is fed through the second stage compressor (6) exiting at an absolute pressure of 1470 psia and a temperature of 713°F where upon it is fed into the burner, an integral part of the direct contact

superheated steam generator (8) to effect the combustion of natural gas. In addition to the preheated superheated steam generator feed water supplied from the inter-stage cooler (3) an additional 445,000 lb/hr of preheated water is pumped by the secondary feed water pump (14) into the direct contact superheated steam generator (8). As a result of the near stoichiometric combustion of the natural gas in the direct contact superheated steam generator (8) 1.5 MM Btu/hr of heat is released and effects vaporization of the water supplied to the direct contact superheated steam generator. As a result, a gaseous mixture consisting predominantly of steam, carbon dioxide and nitrogen exits the superheated steam generator at 1600°F and 1470 psia. This gaseous mixture then passes through the steam turbine (9) to produce work prior to exiting and its subsequent condensation. A portion of the gaseous mixture (63,300 lb/hr) is withdrawn from an intermediate stage in the steam turbine at a pressure of 200 psia and blended in mixer (13) with 383,000 lb/hr of cool condensed water elevated in pressure by pump (12). The mixture of condensate and steam reaches equilibrium at a temperature of 382°F after which it is further elevated in pressure to 1,497 psia by the secondary feed water pump (14) and then injected into the direct contact superheated steam generator. The majority of the vapor mixture entering the power turbine (9) exits at 15 psia and passes through condensor (10) where the temperature is cooled to 200°F. The mixture of hot water and carbon dioxide then passes to a flash separator (11) where the nitrogen and carbon dioxide are vented to the atmosphere, the liquid entering the separator exits through the liquid draw off line and is divided in the flow line tee (15) into the appropriated fractions to be elevated in pressure by either the primary feedwater pump (7) or the secondary feed water pump (14) to the pressure

required for injection into the direct contact superheated steam generator. Power produced by the expanding gases in turbine (9) can be utilized to drive the natural gas and air compressors as well as the three water pumps. The excess energy not required for work in elevating gases and water to the operating pressure of the direct contact superheated steam generator is utilized to produce electric power in the generator (16). A total of 130 megawatts of power is thereby generated, which translates to a conversion efficiency for the primary turbine of 30.1%. A first-stage air compressor utilized in this example is comparable to the air compressor included in the popular General Electric frame six gas turbine power generation machine. For comparison it is noted that this General Electric frame six machine produces only 38 mw of electric power at a published conversion efficiency of 28%. The improvement attributable to this invention is 7.5%, an increment which could save the electric utility industry many millions of dollars in fuel costs annually. The more than three-fold increase in power output could be equally significant for applications where space is a premium, eg. naval ships, urban areas and offshore oil platforms.

The foregoing example is sufficient to detail the thermodynamic improvement resulting from this invention. For simplicity and purposes of illustration only a two-stage compression machine has been described. Increased efficiency in the conversion of thermal energy to electrical energy can be obtained by adding additional compression stages, thus increasing the operating pressure with the result that additional power is generated for every pound of steam that passes through the turbine and also for each pound of fuel consumed. A second and even more dramatic improvement will occur by substituting oxygen enriched air or pure oxygen for the combustion air

used in the foregoing example. By using oxygen it is possible to achieve thermal conversion efficiencies well in excess of 50%, a value completely unobtainable by any technology or combination of technologies now practiced or proposed for the production of electric power. A second advantage to using air enriched in oxygen is that the power output of the turbine is easily modulated by simply adjusting the oxygen content of the gas (air) supplied to the direct contact steam generator, as well as the fuel flow.

WE CLAIM:

1. An improved gas turbine machine that incorporates a combustion chamber designed to burn fuel at a pressure above 500 psia with air, oxygen, or any combination thereof to provide the energy required for direct contact superheated steam generation. The temperature of the gaseous combustion products leaving the combustor is controlled to the desired level by direct cooling achieved by introducing water into or immediately following the combustion zone. The resulting gaseous mixture of combustion products and water vapor or portion thereof is subsequently utilized for the production of power by passage through a suitable turbine.

2. A process according to claim 1 wherein cooling of the combustion gases is accomplished by injection of liquid water into the direct contact superheated steam generator.

3. A process according to claim 1 wherein cooling of the combustion gases is accomplished by injection of steam into the direct contact superheated steam generator.

4. A process according to claim 1 wherein cooling of the combustion gases is accomplished by injecting carbon dioxide in admixture with water (steam) into the direct contact superheated steam generator.

5. A process according to claim 1 wherein cooling of the combustion gases is controlled to produce a gaseous mixture at a temperature above 1000°F.

6. A process according to claim 1 wherein the gaseous source of oxygen supplied to the direct contact

steam generator is pressurized utilizing two or more stages of compression and interstage cooling effected by indirect heat exchange between the compressed gas and the water coolant.

7. A process according to claim 1 wherein the oxygen supplied to the direct contact superheated steam generator is pressurized in the liquid state by means of a cryogenic pump.

8. A process according to claim 1 wherein the gaseous mixture produced in the direct contact superheated steam generator is passed through a gas (steam) turbine exhausting at about atmospheric pressure.

9. A process according to claim 1 wherein the gases exiting the power turbine are condensed by boiling a suitable fluid that is subsequently expanded through a secondary turbine for the production of work energy or power.

10. A process according to claim 1 wherein the oxygen supplied to the direct contact superheated steam generator consists of air enriched with oxygen with the concentration of said oxygen adjusted to control the power output of the turbine.

11. An improved gas turbine machine that incorporates a combustion chamber designed to burn fuel at a pressure above 500 psia with oxygen, to provide the energy required for direct contact superheated steam generation. The oxygen supplied the combustion device will have a purity in excess of 70 volume percent oxygen. The temperature of the combustion products leaving the direct contact superheated steam generator is controlled

to the desired level by direct contact cooling achieved by introducing water into or immediately following the combustion zone. The resulting gaseous mixture of combustion products and water vapor or any portion thereof is subsequently utilized for the production of power by passage through a suitable turbine.

12. A process according to claim 11 wherein cooling of the combustion gases is accomplished by injection of liquid water into the direct contact superheated steam generator.

13. A process according to claim 11 wherein cooling of the combustion gases is accomplished by injection of steam into the direct contact superheated steam generator.

14. A process according to claim 11 wherein cooling of the combustion gases is accomplished by injecting carbon dioxide in admixture with water (steam) into the direct contact superheated steam generator.

15. A process according to claim 11 wherein cooling of the combustion gases is controlled to produce a gaseous mixture at a temperature above 1000°F.

16. A process according to claim 11 wherein the gaseous source of oxygen supplied to the direct contact steam generator is pressurized utilizing two or more stages of compression and interstage cooling effected by indirect heat exchange between the compound gas and coolant feed water.

17. A process according to claim 11 wherein the oxygen supplied to the direct by means of a cryogenic

pump and subsequently vaporized prior to being injected into the direct contact superheated steam generator.

18. A process according to claim 11 wherein the gaseous mixture produced in the direct contact superheated steam generator is passed through a gas (steam) turbine exhausting at about atmospheric pressure.

19. A process according to claim 11 wherein the gases exiting the power turbine are condensed by boiling a suitable fluid that is subsequently expanded through a secondary turbine for the production of work energy or power.

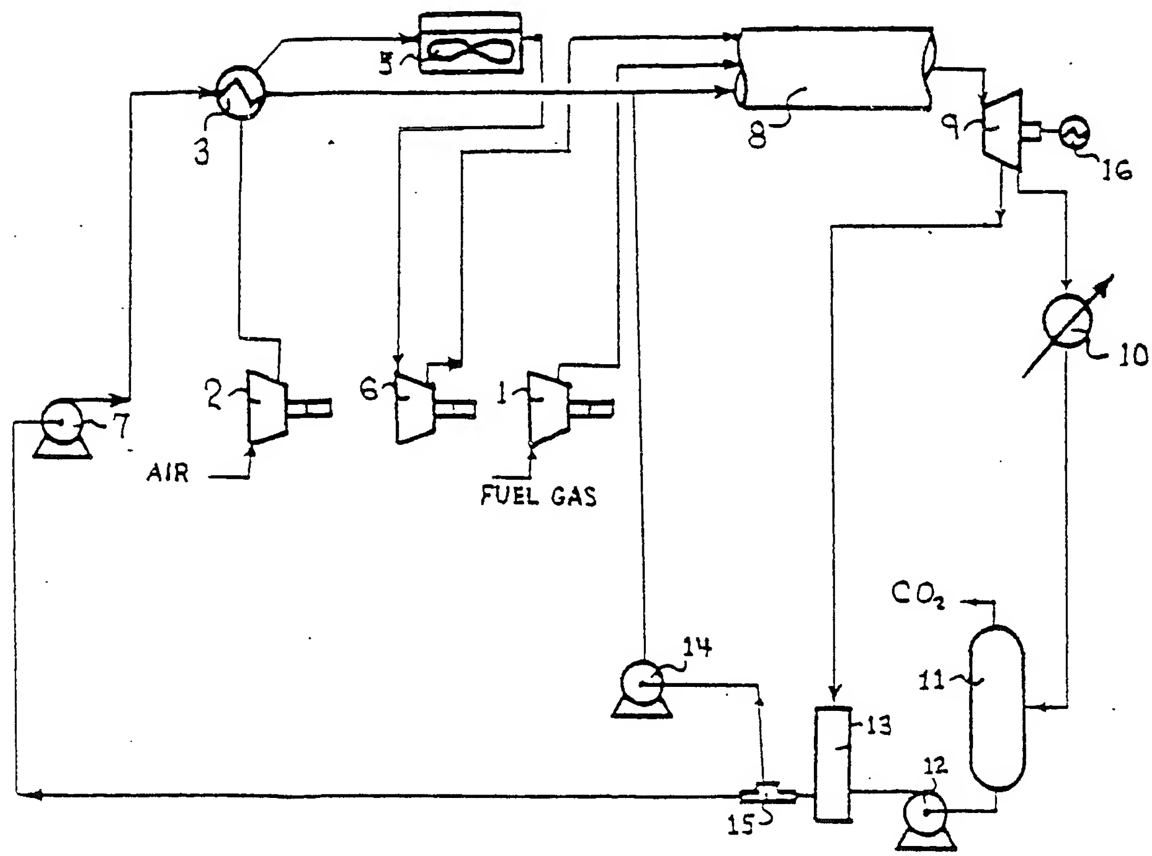

Fig. 1

INTERNATIONAL SEARCH REPORT

International Application No PCT/US86/00256

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int. Cl.[4] F02 C 7/00
US. Cl. 60/39.05, 39.55

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	60/39.05, 39.461, 39.53, 39.55, 39.58

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X	US, A, 3,978,661 07 September 1986 Cheng	1-19
A	US, A, 3,826,080 30 July 1974 De Corso et al	-
X	US, A, 3,693,347 26 September 1972 Kydd et al	1-19
A	US, A, 3,557,879 25 April 1972 Ewabank et al	-
Y	US, A, 3,449,908 17 June 1969 Aguet	6, 16
Y	US, A, 3,134,228 26 May 1964 Wolansky	1-19
A	US, A, 3,038,308 12 June 1962 Fuller	-
X	US, A, 2,469,678 10 May 1949 Wyman	1-19

* Special categories of cited documents: [15]
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IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
25 April 1986	05 MAY 1986
International Searching Authority [1]	Signature of Authorized Officer [20]
ISA/US	L. J. Casaregola by C.R. Croyle L. J. CASAREGOLA / C.R. CROYLE